

Evidence for Shocked Molecular Gas in the Galactic SNR CTB 109 (G109.1–1.0)

Manami Sasaki¹, Roland Kothes^{2,3}, Paul P. Plucinsky¹, Terrance J. Gaetz¹, Christopher M. Brunt⁴

ABSTRACT

We report the detection of molecular clouds around the X-ray bright interior feature in the Galactic supernova remnant (SNR) CTB 109 (G109.1–1.0). This feature, called the Lobe, has been previously suggested to be the result of an interaction of the SNR shock wave with a molecular cloud complex. We present new high resolution X-ray data from the *Chandra* X-ray Observatory and new high resolution CO data from the Five College Radio Observatory which show the interaction region with the cloud complex in greater detail. The CO data reveal three clouds around the Lobe in the velocity interval $-57 < v < -52$ km s⁻¹. The velocity profiles of ¹²CO at various parts of the east cloud are well fit with a Gaussian; however, at the position where the CO cloud and the Lobe overlap, the velocity profile has an additional component towards higher negative velocities. The molecular hydrogen density in this part of the cloud is relatively high ($N_{\text{H}_2} \approx 1.9 \times 10^{20}$ cm⁻²), whereas the foreground absorption in X-rays ($N_{\text{H}} \approx 4.5 \times 10^{21}$ cm⁻²), obtained from *Chandra* data, is lower than in other parts of the cloud and in the north and south cloud. These results indicate that this cloud has been hit by the SNR blast wave on the western side, forming the bright X-ray Lobe.

Subject headings: Shock waves — supernova remnants — ISM: clouds — X-rays: individual (CTB 109)

¹Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; msasaki@cfa.harvard.edu, pplucinsky@cfa.harvard.edu, tgaetz@cfa.harvard.edu.

²National Research Council of Canada, Herzberg Institute of Astrophysics, Dominion Radio Astrophysical Observatory, P.O. Box 248, Penticton, BC V2A 6J9, Canada; roland.kothes@nrc-cnrc.gc.ca.

³Department of Physics and Astronomy, University of Calgary, 2500 University Drive NW, Calgary, AB T2N 1N4, Canada.

⁴School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, United Kingdom, brunt@astro.ex.ac.uk.

1. Introduction

The progenitor stars of core-collapse supernova explosions form in giant molecular clouds. Since these massive stars have a short lifetime many of them end their lives while the parental clouds are still nearby and may even still harbor small star forming regions that produce stars of lower mass. According to Cappellaro et al. (1999) in galaxies like ours about 70% of all supernova explosions are of type II and should explode close to the dense clouds from which they were formed. After these stars explode, strong shocks are driven into the clouds, heating, compressing, dissociating, and accelerating the gas leading to a large variety of observable effects. A picture book example is the Galactic supernova remnant (SNR) IC 443 on which most studies of SNR-molecular cloud interactions have been focused (Seta et al. 1998; Bocchino & Bykov 2000; Kawasaki et al. 2002, and references therein). But recently more and more SNRs have been discovered interacting with molecular clouds, e.g. W28, W44, 3C 391 (e.g., Reach & Rho 2000; Yusef-Zadeh et al. 2003, and references therein), and many others, among them the Galactic SNR CTB 109 (G109.1–1.0).

CTB 109 was first discovered as an SNR in X-rays with *Einstein* (Gregory & Fahlman 1980) and in radio in the 610 MHz Galactic plane survey (Hughes et al. 1981). It has a semi-circular morphology in both the X-ray and the radio and is located next to a giant molecular cloud (GMC) complex in the west. This semi-circular morphology suggests that the SNR shock has been stopped entirely by the GMC complex, and that the appearance is not simply due to absorption. A linear feature in CO (‘CO arm’) extends from the GMC complex to the local X-ray minimum in the northern half (Tatematsu et al. 1987) implying that a part of the GMC complex extends in front of the remnant (see Fig. 1). The cold interstellar medium in which the remnant is embedded has been studied in detail by Kothés et al. (2002). The most puzzling X-ray morphological feature in CTB 109 is the bright, extended interior region known as the ‘Lobe’. The X-ray spectrum from the Lobe obtained with *XMM-Newton* is completely thermal (Sasaki et al. 2004). The Lobe could be the result of a hole in the GMC allowing the X-ray emission through with little or no absorption or it could be the result of intrinsically brighter emission due to an interaction between the shock and the cloud. In order to investigate the later hypothesis we obtained new high resolution X-ray and CO data.

2. Observations

2.1. CO data

Observations of the ^{12}CO and ^{13}CO ($J=1-0$) spectral lines, at $45''$ resolution, were obtained using the Five College Radio Astronomy Observatory (FCRAO) 14 m antenna in March 2003. The telescope was equipped with the 32 element SEQUOIA focal plane array (Erickson et al. 1999). The data were acquired through on-the-fly mapping, in which the telescope was scanned continuously across the sky while reading out the spectrometers at regular intervals of $11''.25$. Calibration to the T_A^* scale was done using the chopper wheel method (Kutner & Ulich 1981), and the data were converted to the radiation temperature scale (T_R^*) by correcting for forward scattering and spillover losses ($\eta_{fss} = 0.7$). The 1024-channel spectrometers were set to a total bandwidth of 25 MHz ($\sim 65 \text{ km s}^{-1}$) centered on -45 km s^{-1} . Following recording of the data, the spectra were converted onto a regular grid of $22''.5$ pixel spacing using the FCRAO *otftool* software.

The new data have higher sensitivity than the CGPS data (Kothes et al. 2002) and are fully Nyquist sampled. The higher sensitivity and the full sampling allow us to detect the faint clouds around the Lobe and study them in great detail.

2.2. Chandra data

The *XMM-Newton* observations have shown that the X-ray bright Lobe is thermal and seem to indicate an interaction between the shock wave and a molecular cloud (Sasaki et al. 2004). Therefore, we proposed an additional deep observation with *Chandra* to probe the shock-cloud interaction region at higher angular resolution. The observation was performed using the Advanced CCD Imaging Spectrometer (ACIS) in full-frame, timed-event mode with an exposure of 80 ksec (ObsID 4626). The data were taken in the energy band of $\sim 0.3 - 10.0 \text{ keV}$. The ACIS-I array covered the northeast part of the SNR and the northern tip of the Lobe was observed at the aimpoint. The data are analyzed with CIAO 3.2.2 and CALDB 3.1.0. The complete analysis of these data including a detailed spectral analysis of the whole area will be presented in a different paper.

Here, we present the high-resolution X-ray image of the Lobe of CTB 109 obtained with *Chandra* ACIS-I. The image is binned with a size of 4 pixels (1 pixel = $0.492''$) and smoothed with a Gaussian with a sigma of 2 pixels (the original pixels binned by 4). X-ray spectra which are extracted at regions corresponding to CO clouds are also discussed, in order to obtain the absorbing foreground hydrogen column density (N_H). The spectra are binned with

a minimum of 50 counts per bin and analyzed using the X-ray spectral analysis tool XSPEC. To fit the spectra, we use a model for a thermal plasma in non-equilibrium ionization with variable abundances (VNEI) and hydrogen column density, N_{H} , for the foreground absorption (PHABS).

3. Discussion

3.1. CO, Infrared, and X-ray Data

In Figure 1 we display the distribution of molecular gas in the vicinity of the X-ray Lobe. In the left image, the CO arm discovered by Tatematsu et al. (1987) is shown. The anti-correlation of the CO emission with the *Chandra* image nicely demonstrates that this molecular cloud is located in the foreground and absorbs the X-ray emission from CTB 109 coming from behind it. In the right panel we averaged the CO emission over a velocity range more negative than that of the CO arm. We can identify three small molecular clouds surrounding the eastern part of CTB 109’s X-ray Lobe with the brightest to the Galactic east (on the left side of the Lobe in Fig. 1, hereafter east) , a fainter one to the Galactic north (above the Lobe, hereafter north) , and another one in the Galactic south (below the Lobe, hereafter south) which is not fully covered by our observations. The noise level in the image is ~ 40 mK. Assuming the progenitor star exploded at or close to the current position of the anomalous X-ray pulsar 1E 2259+586, the location of these clouds is suggestive of an interaction of the SNR shock wave with those molecular clouds resulting in the X-ray Lobe.

Most of the molecular clouds are rather faint in the ^{13}CO line, which is why we cannot perform a detailed comparison with the ^{12}CO measurements. However, we can estimate an average brightness ratio for each of the clouds (see Table 1). The value for the southern cloud is a bit difficult to interpret since it is not fully covered by our observations and it seems to consist of a number of small clouds. We find brightness ratios between 3.5 in the dense part of the CO arm and 13 in the southern clouds. According to Langer & Penzias (1990), at the galactocentric radius of CTB 109 the ^{12}C to ^{13}C isotope ratio r should be about 63. This indicates that we miss some of the ^{12}CO emission and this line is optically thick.

In the following we assume local thermodynamic equilibrium and the same excitation temperature for both isotopic species and all molecules along the line of sight in each cloud. We determine an average optical depth for each cloud in both lines by the following procedure: We use the ^{12}CO to ^{13}CO ratio for each cloud to determine how much ^{12}CO emission we are missing by assuming the ^{13}CO line is optically thin. This can be translated to a first iteration

for the optical depth τ_{12} . If both species have the same excitation temperature the ^{12}CO to ^{13}CO brightness temperature ratio r can be written as: $r = (1 - e^{-\tau_{12}})/(1 - e^{-\tau_{13}})$. From this we determine a first iteration for the optical depth τ_{13} of the ^{13}CO line. This is again used to determine a better value for the missing ^{12}CO emission and so on. This iterative procedure converges usually after just a few iterations. The results for τ_{12} and τ_{13} are listed in Table 1. To integrate the ^{13}CO column density we actually use the ^{12}CO data scaled to ^{13}CO by the brightness ratios for each individual cloud since the signal to noise ratio is higher in our ^{12}CO data. The ^{13}CO column density is then scaled by 5×10^5 to determine the column density of the H_2 molecules N_{H_2} (Dickman 1978). We also estimate H_2 number densities and masses of the clouds (Table 1). While the northern cloud, the southern cloud, and the faint eastern tail of the eastern cloud have comparable H_2 column densities ($< 10^{20} \text{ cm}^{-2}$), the bright part of the eastern cloud that overlaps the Lobe has a higher $N_{\text{H}_2} \approx 1.9 \times 10^{20} \text{ cm}^{-2}$. It is interesting to note that we calculated a peak H_2 column density of $2.2 \times 10^{21} \text{ cm}^{-2}$ for the CO arm, which compares nicely with the value of $2.0 \times 10^{21} \text{ cm}^{-2}$ determined by Tatematsu et al. (1987).

In order to compare with these results, we extract spectra from the *Chandra* data in regions corresponding to the CO clouds and derive the atomic H column density N_{H} in the foreground by fitting the spectrum with a model including a thermal non-equilibrium ionization model and a foreground absorption. For the northern cloud, we obtain $N_{\text{H}} = 6.3 (5.6 - 7.0) \times 10^{21} \text{ cm}^{-2}$ (90% confidence range in parentheses). For the larger eastern cloud, the foreground absorption of the part inside the Lobe is $N_{\text{H}} = 4.5 (4.2 - 4.9) \times 10^{21} \text{ cm}^{-2}$, outside the Lobe, we get $N_{\text{H}} = 5.9 (5.5 - 6.4) \times 10^{21} \text{ cm}^{-2}$, and in the eastern tail the foreground absorption is $N_{\text{H}} = 5.0 (4.2 - 5.4) \times 10^{21} \text{ cm}^{-2}$. Although the N_{H_2} column density is largest in the bright part of the eastern cloud, the foreground N_{H} is the lowest. Therefore, the eastern cloud is not located in front of the Lobe. The foreground absorption in the region of the southern cloud is $N_{\text{H}} = 6.8 (5.8 - 7.3) \times 10^{21} \text{ cm}^{-2}$. The X-ray absorption is significantly higher in the regions corresponding to the northern cloud and the southern cloud than in the eastern tail of the eastern cloud. It seems that these two clouds are located in front of the remnant and absorb some of the X-ray emission.

As the SNR is believed to be located next to the GMC, we assume that both have a systematic velocity of -51 km s^{-1} (Tatematsu et al. 1987; Kothes et al. 2002). The three clouds (radial velocities between -52 and -57 km s^{-1}) are slightly blue-shifted from the GMC to the west, indicating that these clouds are moving towards us relative to the GMC complex. As the bright eastern cloud seems to be related to the X-ray Lobe, we study the velocity profiles of the ^{12}CO emission in different parts of the eastern cloud. This cloud contains the infrared (IR) source IRAS 23004+5841, which has IR colors of a star forming region according to Wouterloot & Brand (1989). Figure 2 compares the profiles taken at

the center of IRAS 23004+5841 (position a) and in the interior of the Lobe (position b, as marked in the right panel in Fig. 1). While the first appears Gaussian, the latter has an additional component towards higher negative velocities. The asymmetry observed in the spectrum suggests that the material has been accelerated by the shock wave of the SNR which traveled into the cloud. The CO line profile is only broadened by a few km s^{-1} which indicates that the acceleration is mostly perpendicular to the line of sight.

The estimated mass of the part of the cloud with the high velocity wing is $3 - 4 M_{\odot}$. We have also taken profiles from parts of the east cloud that do not overlap with the Lobe. The velocity profiles of the northern end of the east cloud and the faint tail in the east show that there is a velocity gradient. The center of the profile changes from -54.8 km s^{-1} to -53.5 km s^{-1} with increasing distance to the Lobe, i.e. the eastern part of the cloud is red-shifted relative to the western part. This gradient indicates an acceleration of the gas in the faint tail away from the eastern cloud. As the gradient starts at the position of IRAS 23004+5841, it might be an outflow from the star forming region.

3.2. The Shocked Cloud

The column densities of H_2 and the X-ray absorbing hydrogen indicate that the northern cloud and the southern cloud are located in front of the X-ray emission. The eastern cloud, however, seems to be linked to the Lobe. Moreover, the CO velocity profile shows an additional blue-shifted component in the eastern cloud where it overlaps the Lobe, suggesting that the cloud has been hit by a shock. The eastern tail of the eastern cloud doesn't show such an additional velocity component and seems to be red-shifted relative to the interacting part of the cloud.

Figure 3 illustrates how the bright eastern CO cloud and the Lobe are possibly located within the remnant. As in such a configuration, the cloud would have a significant velocity component towards us at position b whereas the acceleration is directed perpendicular to the line of sight at position a, a high velocity wing in the velocity profile of the cloud is only observed at position b.

As we believe that the X-ray Lobe was formed by evaporation of a cloud, we estimate the cloud mass from the X-ray emission. We assume that the emission is coming only from the Lobe and that the evaporated cloud now fills a sphere with a radius of $3'$. The XSPEC model VNEI that we use for the spectral fits, gives the normalization $K = [10^{-14}/(4\pi D^2)] \times \int n_e n_H dV$. The mean K per arcsec^2 in the Lobe is $2.0 \times 10^{-7} \text{ cm}^{-5} \text{ arcsec}^{-2}$. For a distance $D = 3 \text{ kpc}$ (Kotthes et al. 2002) and $n_e = 1.2 n_H$, we get $n_H = 0.9 \text{ cm}^{-3}$ and a mass of

$M = 5 M_{\odot}$ for the X-ray gas of the Lobe. The mass of the observed CO clouds are higher than the estimated mass of the evaporated cloud. This could be the reason why the clouds still exist.

4. Summary

We performed observations of ^{12}CO and ^{13}CO as well as a *Chandra* observation of the region around the X-ray Lobe of CTB 109. We have discovered three CO clouds around the Lobe. All three clouds are blue-shifted relative to the GMC in the west of CTB 109. The foreground N_{H} indicates that two clouds in the north and in the south of the Lobe are located in front of the bright X-ray Lobe, whereas the east cloud might be connected to the Lobe. Therefore, the east CO cloud and the X-ray Lobe seem to be evidence for an interaction between the SNR shock wave and a dense cloud. The velocity profiles of the ^{12}CO emission in the east cloud show that there is a velocity gradient in the faint tail in the east, indicating that the eastern part of the cloud is red-shifted. The bright western part of the cloud overlaps with the X-ray Lobe. The ^{12}CO velocity profile at this position has a negative velocity wing indicating an additional acceleration in this part of the cloud. At this position where the CO and the bright X-ray emission overlap, there is also an extended IR source (IRAS 23004+5841) which might be emission from a star forming region. From the new CO and X-ray data we conclude that we have found strong evidence for a shock-cloud interaction at the north-east end of the X-ray Lobe.

Support for this work was provided by the National Aeronautics and Space Administration through *Chandra* Award Number G04-5068X issued by the *Chandra* X-ray Observatory Center, which is operated by the Smithsonian Astrophysical Observatory for and on behalf of the National Aeronautics Space Administration under contract NAS8-03060. The Dominion Radio Astrophysical Observatory is a National Facility operated by the National Research Council of Canada. The Five College Radio Astronomy Observatory is supported by NSF grant AST 01-00793.

REFERENCES

- Bocchino, F. & Bykov, A. M. 2000, A&A, 362, L29
- Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459
- Dickman, R. L. 1978, ApJS, 37, 407

- Erickson, N. R., Grosslein, R. M., Erickson, R. B., & Weinreb, S. 1999, *IEEE Trans. Microwave Theory Tech.*, 47, 2212
- Gregory, P. C. & Fahlman, G. G. 1980, *Nature*, 287, 805
- Hughes, V. A., Harten, R. H., & van den Bergh, S. 1981, *ApJ*, 246, L127
- Kawasaki, M. T., Ozaki, M., Nagase, F., Masai, K., Ishida, M., & Petre, R. 2002, *ApJ*, 572, 897
- Kothes, R., Uyaniker, B., & Yar, A. 2002, *ApJ*, 576, 169
- Kutner, M. L. & Ulich, B. L., 1981, *ApJ*, 250, 341
- Langer, W. D. & Penzias, A. A. 1990, *ApJ*, 357, 477
- Reach, W. T. & Rho, J. 2000, *ApJ*, 544, 843
- Sasaki, M., Plucinsky, P. P., Gaetz, T. J., Smith, R. K., Edgar, R. J., & Slane, P. O. 2004, *ApJ*, 617, 322
- Seta, M., Hasegawa, T., Dame, T. M., Sakamoto, S., Oka, T., Handa, T., Hayashi, M., Morino, J.-I., Sorai, K., & Usuda, K. S. 1998, *ApJ*, 505, 286
- Tatematsu, K., Fukui, Y., Nakano, M., Kogure, T., Ogawa, H., & Kawabata, K. 1987, *A&A*, 184, 279
- Wouterloot, J. G. A. & Brand, J. 1989, *A&AS*, 80, 149
- Yusef-Zadeh, F., Wardle, M., Rho, J., & Sakano, M. 2003, *ApJ*, 585, 319

Fig. 1.— **See f1.jpg.** The distribution of molecular gas in the vicinity of the X-ray Lobe as seen in the light of the $^{12}\text{CO}(1-0)$ line (white contours) overlaid on a *Chandra* image of the X-ray emission between 0.35 and 10.0 keV. (*Left*) The CO data are averaged over the velocity range from -51 to -44.5 km s $^{-1}$ and show the absorbing CO in the foreground. Contours levels are at 0.5, 1.0, 1.5, 2.0, and 2.5 K. The white cross marks the position of the IR source IRAS 23004+5841. The yellow dashed box shows the extent of the region shown in the right figure. (*Right*) The CO data are averaged over the velocity range from -57 to -52 km s $^{-1}$. Contours levels are at 0.15, 0.25, 0.5, 0.8, and 1.2 K. Three clouds are seen Galactic north (up), east (left), and south (down) of the Lobe. The positions at which the velocity profiles in Figure 2 are taken are marked with crosses.

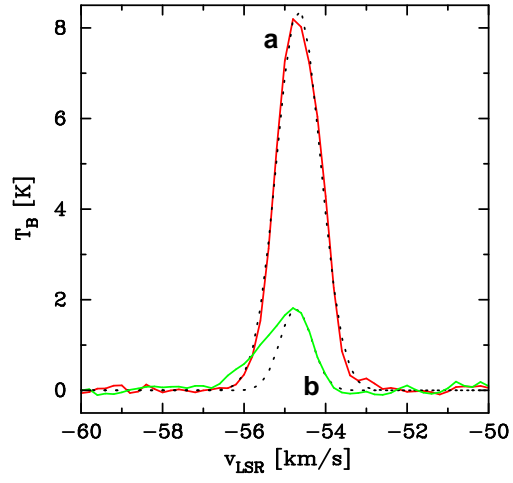


Fig. 2.— Velocity profile of the eastern CO cloud at the position of IRAS 23004+5841 (a) and in the Lobe (b). Solid lines show the data, dotted lines the Gaussian fits.

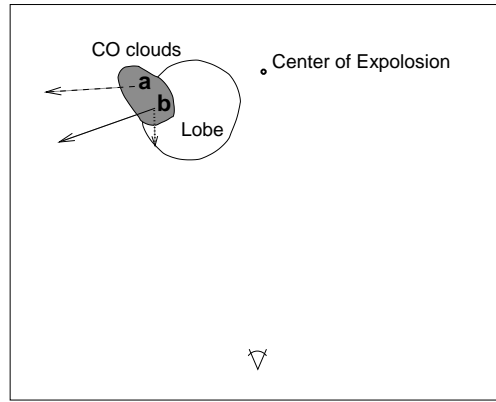


Fig. 3.— Schematic view of CTB 109 showing the Lobe and the eastern cloud. The solid arrow shows the directions to which the part of the cloud at position b has been accelerated. The velocity component directed towards us is shown with a dotted line. As it is not certain how the cloud component at position a is moving in reality, the possible movement of position a is shown with a dashed arrow.

Table 1: Calculated Cloud Characteristics and the Foreground Hydrogen Column Density

Clouds	North	East	Eastern Tail	South	CO arm	Lobe
r	8.1	7.6	12.0	13.0	3.5	...
τ_{12}	2.2	2.2	1.7	1.6	3.2	...
τ_{13}	0.13	0.14	0.076	0.068	0.47	...
N_{H_2} [cm ⁻²]	7.0e19	1.9e20	2.9e19	3.4e19	1.3e21	...
n_{H_2} [cm ⁻³]	10	40	5	2	100	...
Mass [M _⊙]	13	50	3	25	350	...
N_{H} [cm ⁻²]	6.3e21	5.9e21	5.0e21	6.8e21	...	4.5e21

This figure "f1.jpg" is available in "jpg" format from:

<http://arXiv.org/ps/astro-ph/0604164v1>